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Using midday surface temperature to estimate cooling degree-days from NOAA-AVHRR thermal infrared data: An application for Athens, Greece

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Abstract

Cooling degree-days (CDD) are a practical method for assessing the effect ambient air temperature has on the energy performance of buildings. In this study, the relationship between midday land surface temperatures derived from NOAA-AVHRR data and mean daily air temperature observations recorded at standard meteorological stations is defined and statistically validated. The relationship is further used for the calculation of CDD. The benefit of this approach is the direct application of daily satellite data for the definition of CDD in urban areas at a spatial resolution of 1.1 km.

Keywords: Cooling degree-days; Remote sensing; AVHRR

1. Introduction

Degree-days (heating or cooling) are a means of evaluating the energy demand in order to maintain the indoor environment of a building in conditions of human thermal comfort. Cooling degree-days (CDD) are defined as the positive deviation of the mean daily temperature T_m from a base temperature T_b, practically the outdoor ambient temperature above which cooling is activated to sustain the indoor temperature to a comfortable level. The base temperature is an arbitrary but generally accepted temperature and depends on the personal preferences of the people, which live or work in a building. Base temperatures between 10 and 28 °C are usually considered but traditionally, cooling degree-days are determined at the base temperature of 25 °C (Santamouris and Assimakopoulos, 1997). Annual cooling degree-day values are computed from daily CDD values which are summed over a year period. Annual CDD, however, tend to accrue primarily during the warm summer months.

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The energy demand of a building is influenced by a number of different climatic factors such as air temperature, solar radiation, humidity and wind and it is mainly dependent on the construction details and architectural design of a building. Cooling degree-days are the most common practical method for assessing the effect of air temperature on the energy performance of a building and they are used as a reasonable approximation of the cooling energy needs of a city with respect to it. Knowledge of the spatial distribution of CDD in a city allows for the description and mapping of the temperature conditions within the urban web. This information may be high of interest to urban planners and climatologists, as the application of such knowledge can attribute to the improvement of the urban environment and the decrease of energy consumption in cities, since location-specific standards for thermal insulation can be determined to ensure satisfactory energy performance of buildings. In addition, knowledge of the spatial variations of CDD in a particular region can be utilized by civil engineers and architects as a rule of thumb evaluation of the local environment during early design stages of a building.

From studies calculating the cooling load of buildings for the city of Athens in Greece (Hassid et al., 2000; Santamouris et al., 2001), it is found that during summer noon hours the cooling load of urban buildings at the city center is about double compared to the respective load in the surrounding Athens area; the peak electricity load for cooling purposes may be tripled especially for set point temperatures higher than 26 °C, whereas the minimum coefficient of performance (COP) value of air conditioners may be decreased up to 25% because of the high ambient temperatures in the central area of Athens. Another study for the area of Greece (Cartalis et al., 2001) showed that a significant increase in cooling degree-days and thus in energy demand is expected for the coming years for cooling needs during spring and summer period. It is found that the areas most affected in terms of increases in the CDD are the Greater Athens Area, central Macedonia regions, the Aegean islands and Crete island.

According to their definition, cooling degree-days (CDD) are calculated as:

$$\mathrm{CDD} = (1\ \mathrm{day}) \sum_{\mathrm{days}} (T_{\mathrm{m}} - T_{\mathrm{b}})^{+}, \tag{1}$$

where T_b is the base temperature and T_m is the mean daily outdoor temperature. The plus sign (+) of the equation indicates that only positive values are to be counted, meaning that if $T_m < T_b$ then CDD = 0. For example, using a base temperature of 25 °C and considering a day with a mean temperature of 30 °C, then a value of 5-degree cooling days is obtained from Eq. (1) for the given day. Daily values of CDD are summed to calculate the total number of cooling degree-days over a period in question. In the event that the mean daily temperature hourly measurements of the outdoor air temperature were used, the cooling degree-hours (CDH) may be calculated. Tselepidaki et al. (1994) examined the relation between CDD and CDH and found that a strong linear correlation exists, thus CDH can be estimated accurately on the basis of CDD values.

Other methods for assessing CDD can be also found in the literature. Calculation of CDD can be achieved by using monthly-average daily temperatures (Erbs et al., 1983) as well as monthly-average solar radiation and ambient temperature data in combination (Erbs et al., 1984). At an earlier study, Thom (1957) proposed the calculation of cooling degree-days based on the positive deficit of the discomfort index (DI) value from the suggested base temperature value of 15.6 °C. There are also relatively more complicated methods based on the comparison of the daily pattern of the air temperature (T_m, T_{min}, T_{max}) with the base temperature. By applying one of these CDD methods, many cooling degree-day studies have been performed for different cities, regions or countries worldwide (Badescu and Zamfir, 1999; Buyukalaca et al., 2001; Said, 1992; Tselepidaki et al., 1993; Crawley et al., 1994; Al-Homoud, 1998) and CDD results were utilized for a reasonable evaluation/prediction of the energy consumption for cooling purposes.

However, a limitation of the CDD methods mentioned above relates to the lack of ground data, both in terms of spatial and temporal coverage. Even in the most developed countries, it is rare the average separation of the stations to be less than 1 km. Data from only two or three ground stations which are usually several kilometres apart from each other, fail to describe the spatial heterogeneity over urban areas as there are strong microscale variations in the main climatic variables such as air temperature, solar radiation, moisture (humidity and precipitation) and winds (Oke, 1978; Santamouris and Assimakopoulos, 1997). Many studies of the urban microclimate, including several of Athens itself (Mihalakakou et al., 2004; Stathopoulou et al., 2004; Livada et al., 2002; Santamouris et al., 1999), have found substantial differences in air temperature among sites less than 1 km apart, indicating that the actual CDD of a site may be different from a regional average value. In addition, data from ground meteorological stations are either unavailable or often deficient.

Satellite remote sensing provides better spatial coverage than do surface meteorological data, in view of the fact that satellite data are more spatially contiguous and available over much of the earth on a regular basis. The National Oceanic and Atmospheric Administration (NOAA) series of meteorological satellites are in a sun-synchronous orbit at an average altitude of 833 km, having the advantage of covering the same area twice in each 24-h period with a spatial resolution of 1.1 km at the nadir (Lillesand and Kiefer, 1987). The Advanced

Very High Resolution Radiometer (AVHRR) sensor, on board the NOAA satellite series, acquires five spectral channels from which two (channel 4 and 5) are located in the thermal infrared region (10.3–12.5 μm) and thus, they are widely used for retrieval of the surface temperature.

A number of algorithms have been proposed to derive main climatic variables such as air temperature, precipitable water, near-surface water vapour and soil moisture from the NOAA AVHRR observations (Prince et al., 1998; Czajkowski et al., 2002; Chrysoulakis and Cartalis, 2002; Prihodko and Goward, 1997; Choudhury and DiGirolamo, 1995; Sandholt et al., 2002). In most cases, the variables are related to the surface temperature derived from the AVHRR thermal data. Thus, the accuracy of the estimated variables derived by the above algorithms depends on the accuracy of the retrieved surface temperature. In particular, algorithms to estimate surface temperature and near-surface air temperature from AVHRR thermal data have produced reasonable results with ±2 K error for surface temperature and ±3 K error for air temperature (Prata, 1993; Caselles et al., 1997; Kerr et al., 1992; Ouaidrari et al., 2002; Czajkowski et al., 1997; Prihodko and Goward, 1997). The desired accuracy for surface temperature estimates, as expressed by the NASA terrestrial science community, is 1 K (NASA, 1991). Air temperature is more difficult to determine from remotely sensed data, because of its strong dependence on the surface properties that vary significantly both in space and time, especially over urban areas (Voogt and Oke, 1997). Thus, satellite surface temperatures often overestimate coincident actual screen level air temperatures during the daytime (Creswell et al., 1999). However, if a correlation between satellite midday surface temperatures and mean daily air temperatures as recorded by the standard meteorological stations can be achieved, a reasonable estimate of spatial patterns of cooling degree-days from remotely sensed data should be possible. Their combined use with the temporal sufficient ground data would facilitate current research on evaluation of the energy needs of cities for cooling purposes and at the same time eliminate reliance on surface meteorological data.

The aim of the study is twofold: firstly to define a valid relationship in between midday land surface temperatures as deduced from NOAA-AVHRR thermal infrared data to mean daily air temperatures and secondly to utilize this relationship so as to estimate the cooling degree-days, the latter considered a key parameter in the evaluation of the energy consumption in cities. For the needs of the study, a surface temperature threshold as emerged from the correlation between midday surface temperature and mean daily air temperature is defined and further used for the estimation of CDD from daily satellite data. Results are compared with CDD values obtained from standard meteorological stations on the acquisition dates of the satellite overpasses. The study area is the metropolitan city of Athens, Greece.

2. Methodology

2.1. Surface temperature retrieval from NOAA-AVHRR data

Fifty NOAA-14 AVHRR daytime images covering the city of Athens in Greece for the period from June to August 2000 were collected for the purposes of this study. NOAA-14 of the NOAA satellite series was selected because it provides images over the study area that are scanned at around 14:00 UTC hours, therefore are well suited to estimate midday surface temperatures. At a first step, the 1×1 km images were radiometrically and geometrically corrected. Radiometric correction was achieved by applying the radiance-based procedure set by NOAA (Kidwell, 1998). In this way, raw digital number (DN) values are converted to radiance and radiance is further converted to reflectances for channels 1 (0.58–0.68 μm) and 2 (0.725–1.10 μm) and to brightness temperatures for the thermal channels 4 (10.3–11.3 μm) and 5 (11.5–12.5 μm). The latter conversion was performed using the inversion of Planck's radiation equation.

Following, all NOAA-14 AVHRR images were registered to the Universal Transverse Mercator (UTM) coordinate system using 10 ground control points (GCPs) and were rectified with a root mean square error (*rmse*) of about 1 pixel. At a next step, a cloud mask derived from histogram evaluation of the channel 1 reflectance was applied; pixels with channel 1 reflectance greater than 25% were considered cloud contaminated and rejected. Thus, of the potential 50 NOAA-14 AVHRR images collected, 32 images corresponding to clear sky conditions were further analyzed. Table 1 shows the list of the cloud-free midday NOAA-14 AVHRR images used in this study.

Channels 4 and 5 were used to calculate surface temperature by applying the split-window algorithm outlined by Czajkowski et al. (1998), which corrects for the effects of the sensor filter functions. The impact of filter functions is an important aspect when using a split-window algorithm, especially for the NOAA-AVHRR satellite series. For the surface temperature estimation, numerous split-window algorithms (Dash et al., 2002) have been developed by authors using data from one AVHRR sensor: AVHRR on NOAA-7 (Price, 1984), AVHRR on NOAA-9 (Becker and Li, 1990), AVHRR on NOAA-11 (Sobrino et al., 1991), etc. The filter functions for AVHRR channels 4 and 5 differ slightly for each sensor in the NOAA series, which results in different split-window coefficients; if this is not accounted for,

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Table 1
List of cloud-free midday NOAA-14 AVHRR images used in the present study

Acquisition date (d/m/y)	Acquisition time (UTC)
10/06/2000	14:12
11/06/2000	14:00
12/06/2000	13:48
18/06/2000	14:20
20/06/2000	13:56
21/06/2000	13:44
25/06/2000	14:39
26/06/2000	14:28
27/06/2000	14:16
28/06/2000	14:04
29/06/2000	13:52
04/07/2000	14:35
05/07/2000	14:23
06/07/2000	14:11
07/07/2000	13:59
08/07/2000	13:48
12/07/2000	14:42
15/07/2000	14:07
24/07/2000	14:03
25/07/2000	13:51
30/07/2000	14:34
01/08/2000	14:10
07/08/2000	14:41
10/08/2000	14:06
15/08/2000	14:48
16/08/2000	14:36
17/08/2000	14:25
18/08/2000	14:13
19/08/2000	14:01
24/08/2000	14:43
25/08/2000	14:32
27/08/2000	14:08

using a split-window algorithm can result in a considerable error in the surface temperature estimation of about 2.3 K (Czajkowski et al., 1998). In comparison, inaccuracies in satellite calibration and precision may cause an error of 0.3 K (Cooper and Asrar, 1989) and variations in surface emissivity (of about 2%) may produce an error of 1 K (Ottlé and Vidal-Madjar, 1992).

Using the Czajkowski et al. (1998) algorithm with the split-window coefficients for the NOAA-14 AVHRR, surface temperature T_s was obtained from AVHRR data. T_s is given as:

$$T_s = 5.54 + T_4 + 2.08(T_4 - T_5), \quad (2)$$

where T_4 and T_5 are the brightness temperatures of the AVHRR channels 4 and 5, respectively, both measured in Kelvin degrees.

2.2. Relationship between midday surface temperature and daily air temperature

Following the retrieval of the midday surface temperature from the NOAA-14 AVHRR data, the relationship between T_s estimated on the basis of Eq. (2) and mean daily air temperature (as recorded at standard meteorological stations) was examined. Ground measurements of hourly data (air and soil temperature) were obtained from the two representative meteorological stations of Thissio (37°58′N, 23°43′E) and Penteli (38°03′N, 23°51′E), both operated by the National Observatory of Athens (NOA) and located within the study area; the Thissio station is located in the central area of Athens (altitude = 107 m), whereas the Penteli station is placed in the northeastern area of Athens (altitude = 509 m) in a suburban region. For both stations, the mean daily air temperature is calculated using the hourly air temperature measurements (T_i) from Eq. (3):

$$T_m = \left(\sum_{1}^{24} T_i\right) \Big/ 24. \quad (3)$$

Next, the values of T_m as computed from Eq. (3) were plotted against stations midday (at 14:00 h UTC) soil temperature values so as to examine whether a direct relationship in between these parameters can be scientifically be justified. Results are demonstrated in Fig. 1, from which it is clear that a linear correlation in between mean daily air temperature and midday soil temperature is feasible.

In fact, this relation was the starting point for further research, namely so as to investigate the correlation between mean daily air temperature (from station data) and midday surface temperature (from AVHRR data) with the scope of utilizing this correlation in order to estimate CDD from remote-sensed surface temperatures. To achieve this, at a next step, the values of the mean daily air temperature (from both meteorological stations) were compared to the AVHRR-retrieved val-

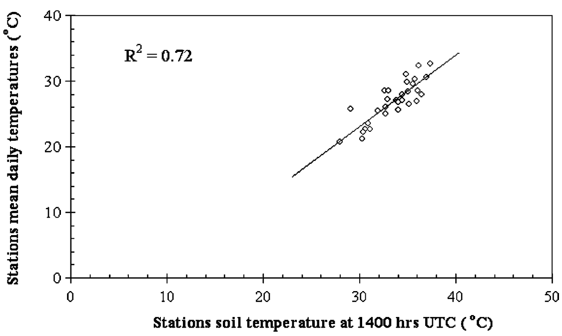

Fig. 1. Relationship between mean daily air temperatures and midday (at 14:00 h UTC) soil surface temperatures from observations obtained from the Thissio and Penteli stations.

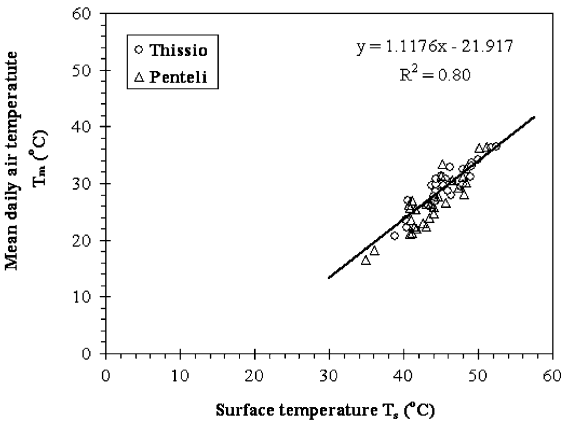

Fig. 2. Comparison of mean daily air temperatures (from station data) and AVHRR-retrieved midday (14:00 UTC) surface temperatures on all acquisition dates of the AVHRR images.

ues of T_s for all acquisition dates of the cloud-free NOAA-14 AVHRR images (Fig. 2). It must be mentioned that the T_s values used in the comparison were the surface temperatures of the pixels corresponding to the location of the meteorological stations.

Regression analysis showed the mean daily air temperature to be highly correlated ($R^2 = 0.80$) with midday AVHRR surface temperature. Thus, it is concluded that a direct relationship between T_m and T_s can be established which is expressed as:

$$T_m = 1.1176T_s - 21.917 \quad (\text{in } ^\circ\text{C}), \tag{4}$$

where T_m is the mean daily air temperature (from station data) and T_s is the midday surface temperature as derived from the AVHRR data. From Eq. (4), a surface temperature threshold can be determined defined as a "surface base temperature" T_{sb} in terms of the base temperature value and used in a concept analogous to the latter in order to estimate CDD from remotely sensed data. For example, if for a given day the midday AVHRR-retrieved surface temperature of a location exceeded the "surface base temperature", then the CDD value for this location would be estimated by the positive deviation of the surface temperature to the surface base temperature. Therefore, by solving Eq. (4) for T_s and replacing $T_m = 25$ °C, a surface base temperature value of 42 °C is retrieved and it is further adopted for estimating CDD from NOAA-AVHRR data.

2.3. Actual and AVHRR-estimated cooling degree-days

Actual cooling degree-days (CDD_a) were computed from the air temperature data recorded at the two meteorological stations on all acquisition dates of the AVHRR images listed in Table 1 and by adopting the base temperature of 25 °C. In this manner, daily results of the CDD_a were given as:

$$CDD_a = T_m - T_b, \tag{5}$$

where, T_m is the mean daily air temperature as computed from Eq. (3) and T_b is the base temperature of 25 °C. The CDD_a values obtained were used as *in situ* data and then compared with the AVHRR-estimated CDD values (CDD_{est}) in order to validate the method.

Estimated cooling degree-days (CDD_{est}) from the AVHRR surface temperature data were calculated in a similar way. Therefore, daily results of the CDD_{est} were obtained from the following equation:

$$CDD_{est} = T_s - T_{sb}, \tag{6}$$

where T_s is the midday AVHRR-retrieved surface temperature (in °C) and T_{sb} is the surface base temperature of 42 °C. The use of Eq. (6) is supported by the high correlation coefficient ($R^2 = 0.80$) of Eq. (4).

3. Results and discussion

Statistical results between estimated and actual CDD values for the meteorological stations of Thissio and Penteli are depicted in Tables 2 and 3, respectively. In both Tables, column 1 shows the daily estimated CDD as derived from the AVHRR surface temperature data, whereas column 2 lists the corresponding daily results of the actual CDD for the respective meteorological station.

Comparison between estimated and actual CDD values for both meteorological stations at the base temperature of 25 °C, showed an overall strong correlation between CDD_{est} and CDD_a (Fig. 3). The produced coefficient of determination (R^2) had the value of 0.78. Further, the slope of the regression line between estimated (CDD_{est}) and actual (CDD_a) cooling degree-day values is lower than 1 ($CDD_{est} = 0.74\,CDD_a + 0.37$), suggesting that there is a tendency to underestimate CDD with increasing actual CDD. The mean absolute error had a value of 1.36-degree cooling days for the Thissio station and 1.14-degree cooling days for the Penteli station. In addition, a root mean square error (*rmse*) of 1.68 and 1.67 degree cooling days were obtained for the Thissio and Penteli stations, in respective.

It is evident from Tables 2 and 3 that there is a satisfactory agreement between estimated and actual CDD values in terms of the base temperatures excess. Seventy-one percent of the estimated zero CDD values agreed with the actual zero CDD values. Moreover, 81% of the estimated CDD were within 2-degree cooling days of the actual CDD, whereas only 10% of the estimated CDD values exceeded the actual CDD values more than 3-degree cooling days.

Table 2
Daily results of estimated and actual CDD for the Thissio station

Date (d/m/y)	CDD_{est}	CDD_a	ΔCDD (est − act)
10/06/2000	5.7	4.5	1.2
11/06/2000	1.7	1.4	0.3
12/06/2000	2.4	1.9	0.5
18/06/2000	0	0	0
20/06/2000	0	0	0
21/06/2000	0	0	0
25/06/2000	7.0	6.1	0.9
26/06/2000	4.5	5.3	−0.8
27/06/2000	4.4	3.0	1.4
28/06/2000	1.9	0.6	1.3
29/06/2000	2.2	1.8	0.4
04/07/2000	8.0	9.2	−1.2
05/07/2000	9.8	11.3	−1.5
06/07/2000	10.5	11.4	−0.9
07/07/2000	7.1	8.6	−1.5
08/07/2000	7.1	8.1	−1.0
12/07/2000	3.1	6.3	−3.2
15/07/2000	1.3	1.0	0.3
24/07/2000	3.9	3.6	0.3
25/07/2000	6.0	7.4	−1.4
30/07/2000	2.3	3.6	−1.3
01/08/2000	2.0	2.7	−0.7
07/08/2000	5.9	4.9	1.0
10/08/2000	2.6	4.6	−2.0
15/08/2000	3.6	5.8	−2.2
16/08/2000	2.5	5.0	−2.5
17/08/2000	3.4	4.7	−1.3
18/08/2000	1.8	4.7	−2.9
19/08/2000	2.3	4.8	−2.5
24/08/2000	4.2	7.9	−3.7
25/08/2000	2.4	5.7	−3.3
27/08/2000	0	1.9	−1.9

Table 3
Daily results of estimated and actual CDD for the Penteli station

Date (d/m/y)	CDD_{est}	CDD_a	ΔCDD (est − act)
10/06/2000	2.0	0	2.0
11/06/2000	0	0	0
12/06/2000	0	0	0
18/06/2000	0	0	0
20/06/2000	0	0	0
21/06/2000	0	0	0
25/06/2000	5.4	4.2	1.2
26/06/2000	6.1	3.1	3.0
27/06/2000	0	0	0
28/06/2000	0	0	0
29/06/2000	1.0	0	1.0
04/07/2000	6.4	7.6	−1.2
05/07/2000	9.2	11.4	−2.2
06/07/2000	8.2	11.2	−3.0
07/07/2000	6.4	5.1	1.3
08/07/2000	6.0	6.1	−0.1
12/07/2000	3.2	8.4	−5.2
15/07/2000	0.6	0	0.6
24/07/2000	2.7	2.7	0
25/07/2000	4.5	5.5	−1.0
30/07/2000	2.1	0.9	1.2
01/08/2000	1.5	0	1.5
07/08/2000	3.6	1.6	2.0
10/08/2000	0	0.4	−0.4
15/08/2000	0	1.9	−1.9
16/08/2000	0	0.6	−0.6
17/08/2000	1.0	1.3	−0.3
18/08/2000	1.6	1.4	0.2
19/08/2000	0	1.2	−1.2
24/08/2000	3.1	6.4	−3.3
25/08/2000	0	2.0	−2.0
27/08/2000	–	–	–

If a higher base temperature was adopted, for example that of 28 °C, the induced "surface base temperature" would increase to 45 °C. The methodology was repeated using this time a T_b value of 28 °C and a T_{sb} value of 45 °C and the results were depicted in Fig. 4. In this case, the correlation between CDD_{est} and CDD_a was also positive but rather weak, ($R^2 = 0.6$) indicating that the methodology cannot be applied at the base temperature of 28 °C. The weaker correlation may be attributed to the underestimation of the CDD values as deduced from AVHRR surface temperatures, a fact which in turn is due to the saturation of the thermal infrared during days in August with extremely high temperatures.

With the use of this approach, it appears possible to estimate daily CDD with an error of about 1.7-degree cooling days. This accuracy is affected by the precision with which surface temperature may be estimated from the AVHRR remotely sensed data. For example, an er-

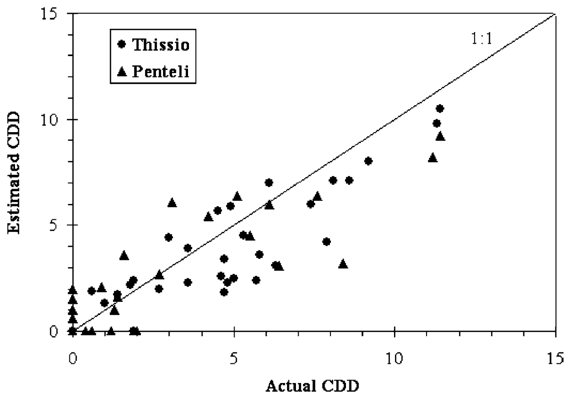

Fig. 3. Scatterplot of estimated versus actual cooling degree-days on all acquisition dates of the AVHRR images and for both meteorological stations at the base temperature of 25 °C, $y = 0.3679 + 0.741x$, $R^2 = 0.78$. The perfect prediction line is also plotted and labelled (1:1).

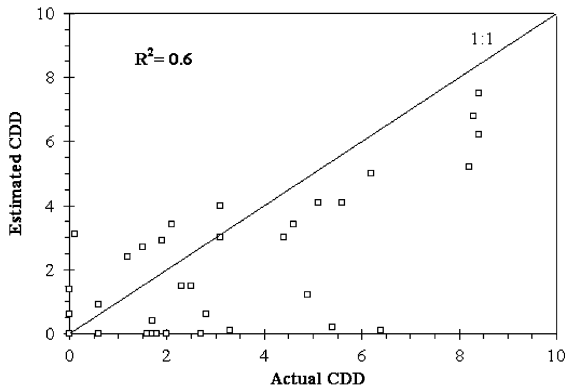

Fig. 4. Estimated versus actual cooling degree-days for both meteorological stations and on all acquisition dates of the AVHRR images at the base temperature of 28 °C.

ror of ±2 °C in the AVHRR surface temperature can lead to an error of 2.2-degree cooling days in CDD estimations.

Although remotely sensed CDD estimates have the advantage of the spatial coverage across large urban areas, depicting thus effectively the variations in CDD that exist between different urban sites, they are constrained by interference by clouds. On the other hand, CDD measurements from standard meteorological stations hold spatial coverage limitations nevertheless can provide excellent temporal records. However, the area-integrated satellite CDD estimates derived from observations of the entire field of view of the radiometer (1×1 km^2) are generally more areal than a single point measurement of CDD which corresponds to the location of the standard meteorological station. For example, the average range in the mean daily air temperature between the two meteorological stations of Thissio and Penteli was about 3 °C, indicating that the selection of any one ground station to represent an urban area would mask any spatial variations in air temperature and consequently in CDD within the urban web.

It is concluded that the remotely sensed CDD estimates should be used in combination with the observed CDD values acquired from an urban meteorological station network, since the methods they originate from are complementary.

4. Conclusions

In this study, an attempt was made to estimate the cooling degree-days from NOAA-AVHRR surface temperatures at a spatial resolution of 1.1 km. The study area was the metropolitan city of Athens, Greece. Estimated cooling degree-days were obtained based on the surface temperature excess from a surface base temperature, which was determined from an empirical expression that relates midday AVHRR surface temperature with daily air temperature as recorded at standard meteorological stations.

From the statistical analysis between estimated and actual CDD a mean absolute error of 1.4-degree cooling days for the Thissio station and that of 1.1-degree cooling days for the Penteli station were deduced. The methodology showed good results in terms of consistency with the base temperature excess for the case of 25 °C, contrary to the case that a base temperature of 28 °C was employed.

The initial findings are encouraging and support the direct and daily definition of CDD at a spatial resolution of 1.1 km and for urban sites which are not adequately covered by meteorological stations. It should be noted that the empirical expression between midday AVHRR surface temperature and daily air temperature as well as the deduced value of the surface base temperature were obtained from using ground data, thus are of local validity. However, since the only data required are the cost-free NOAA-14 AVHRR midday images and daily air temperatures from ground stations, the proposed methodology can be applied in all urban areas.

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